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A TRANSIENT EXPERIMENT USING A MULTIPLE-PULSE LASER LIGHT SOURCE

Fritz H. Oertel, Jr.

September 1976

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We applied a technique of passively Q-switching a ruby laser to photograph transient development of an unsteady, underexpanded jet. In this technique, a bleachable absorber was used to generate multiple laser pulses which backlighted a Mach-Zehnder optical interferometer used to observe the jet flow; instantaneous images of the laser-illuminated event were swept onto a fixed film drum by a mirror rotating at ∿ 75,000 RPM for a film writing speed of ∿ 16mm/μs.

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Our success ratio, which was good, was achieved despite the fact that control of pulse separation, number of pulses, duration of lasing action, and pulse-to-pulse intensity was not precise. We had more success with the passive technique than we did with an electronic, high voltage technique--described in the report--for multiple Q-switching of a Pockels cell.

[redacted]

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I. INTRODUCTION

The purpose of this report is to describe an experimental technique using a laser light source which we have used to obtain several photographs of the development of a transient flow field for a single run.[1] In our experiment, which we will describe in more detail later, a shock wave leaves a cylindrical tube to expand into a low pressure test section. Behind the shock wave, an underexpanded jet forms. The characteristic time for jet formation depends on tube diameter and on the initial conditions of the gas at the tube exit; for the cases we are interested in, this time is 100μs or less. We want to make qualitative observations *and* quantitative measurements during this highly transient event.

To follow the development of such a flow field *qualitatively*, it is sufficient to photograph the flow at different times for separate runs using optical flow visualization techniques, such as: shadow, schlieren, and interference. However, to make *quantitative* measurements, it is advantageous--and for some experiments even critical--to obtain sets of data for single runs so that run-to-run variations of initial conditions won't cloud interpretation of the data.

To obtain *quantitative* data, we chose to make sets of interferograms for each run. From each interferogram, made for different stages of flow development, we can, in principle, map the instantaneous contours of constant density for the entire flow field; moreover, these measurements are made without disturbing the flow.

The fast recording speed needed to make photographs during the development of such a highly transient flow field imposes a severe restriction on the 'framing rate' of the camera and on the light source's repetition rate, intensity, and pulse duration. In the following sections, we will describe our technique for obtaining the desired optical data for the jet flow described briefly in the first paragraph. Central to the technique is a multi-pulse laser light source using a low-cost Q-switch that should be attractive to other experimenters who need to obtain optical information about transient phenomena.

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1. *F. H. Oertel, Jr., "Laser Interferometry of Unsteady, Underexpanded Jets," Proc. Int'l. Cong. Instr. in Aerospace Simulation Facilities, California Institute of Technology, Pasadena, CA, p. 146, 1973; also published as Ballistic Research Laboratories Report No. 1694, January 1974, AD 773664.*

II. EXPERIMENT

Major components of the experimental apparatus are: the shock tube,[2] laser light source, Mach-Zehnder optical interferometer,[3,4,5] other optics, and high speed camera. They are shown in schematic in Figure 1.

A. Flow Facility*

Figure 2 shows dimensions in the immediate vincinity of the shock tube's test section. The facility was converted to do this experiment by adding the 25.4mm diameter smoothbore tube ("jet tube") and mounting plate shown.

For the experiment reported here, air pressure in the "jet tube" and test section--isolated from the shock tube by the mounting plate and a diaphragm (see Figure 2)--was reduced to 0.027 atmospheres (atm) so that the fringeshift[3,5] on the interferograms would be measurable. The shock tube driven section contained air at 0.41 atm.

The test flow, generated by the rupture of a diaphragm between the shock tube's driver and driven sections (not shown-upstream on Figure 2), was initiated by a combustion-heated helium driver.[2] When the diaphragm ruptured, a shock wave propagated into the shock tube to reflect from the mounting plate. A scribed aluminum diaphragm ($\sim$ 0.8mm thick with an unsupported area of 25.4mm diameter) sealing the end of the tube was selected to open under the force exerted by

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2. *J. H. Spurk, E. J. Gion, and W. B. Sturek, "Modified Expansion Tube," AIAA Journal, Vol. 7, No. 2, 1969; also published as Ballistic Research Laboratories Report No. 1404, June 1968, AD 673109.*

3. *H. W. Liepmann and A. Roshko, Elements of Gasdynamics, Galcit Aeronautical Series, John Wiley and Sons, Inc., New York, 1960, 3rd Ed., pp. 164-168.*

4. *R. L. Rowe, "Interferometers for Hypervelocity Ranges," ISA Trans., Vol. 5, No. 1, 1966.*

5. *R. Ladenburg, C. C. Van Voorhis, and J. Winckler, "Interferometric Studies of Faster than Sound Phenomena. Part II. Analysis of Supersonic Air Jets," Phys. Rev., Vol. 76, No. 5, 1949.*

**The shock tube portion of the flow facility has been described in the literature as an expansion tube[2]. It was converted to operation as a shock tube by removing its secondary diaphragm, and to a jet flow simulator as described above.*

the stagnated flow. After the diaphragm opened, a shock wave propagated through the tube--as in a shock tube--to exit from the tube into the viewing plane of the windows. Our photographs will show this in-tube normal shock as it expands into the receiver gas becoming nearly spherical, and the evolution of the jet flow behind it.

Figure 3 shows an oscilloscope trace of the static pressure measured by an electrically-isolated, calibrated piezoelectric pressure gage shock-mounted in the wall of the tube 3.97mm from the exit plane. Passage of the shock is indicated by an abrupt increase in amplitude. Pressure remains constant as the shock-heated air flows past, followed by the cooler air behind the contact front. As waves arrive from upstream, the pressure is seen to increase. The sequence of laser pulses for this run is also shown on the trace. The shape of each laser pulse is due to saturation of the photoelectric diode (solar cell) used to record the pulses. In reality, laser pulse duration is ∿ 30ns. How the pulses are generated will be discussed in the next section.

B. Sequence Laser Q-Switching

Work has been done to develop the laser as a multiple pulse light source for studying transient physical phenomena (Reference 6 lists some of the development work, including applications). Regardless of the method of Q-switching--electro-optic, acousto-optic, mechanical, or passive--separation between pulses is usually limited by the time required for flashlamp pumping to reestablish a population inversion in the laser rod high enough above threshold that oscillations may occur. This time of recovery after a pulse depends on the energy of the pulse; it is at least 10 μs after a giant pulse.[7] Consequently, the lasing energy extracted per pulse must be kept low if several pulses are to be generated in a short time. These restrictions normally limit sequence laser operation to low energy pulses separated by several microseconds. The energy density of such pulses is usually more than enough for use as a photographic light source. For our purposes, we considered electrical and passive Q-switching.

Solid-state, electrically-operated shutters (Pockels cells) use a crystal which is normally uniaxial, but becomes birefringent when subjected to an electric field. For the ruby laser, whose output is plane polarized, the Pockels cell is normally placed in the laser

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6. *R. E. Rowlands and C. E. Taylor, "Pulsed Laser High-Speed Photography," Proc. Int'l, Cong. Instr. in Aerospace Simulation Facilities, Polytechnic Institute of Brooklyn, Farmingdale, New York, p. 145, 1969.*

7. *B. A. Lengyel, Lasers, Wiley-Interscience, John Wiley & Sons, Inc., New York, N.Y., 1971, 2d Ed., p. 174.*

cavity behind the laser head (where the dye cell is on Figure 1) with an analyzer (Brewster stack) between the cell and the 100% reflector. Gain of the cavity is positively-controlled by orienting the analyzer so that the polarized emissions from the laser rod are rejected by the analyzer except when the proper voltage is applied to the crystal (pulse-on-mode). When proper voltage is applied, the path to the 100% reflector is open and oscillations leading to a giant pulse can occur.

During our brief excursion into high voltage, multiple-pulse Q-switching, we generated two sequential giant pulses using the matched parallel circuits shown in Figure 4. Two capacitors charged to 7.5 KV were discharged in sequence--with a minimum time separation in the delay generator of $\sim$ 10 μs--through the primaries of a pulse transformer to deliver two 15 KV pulses to the AD*P (ammonium dihydrogen phosphate) crystal Pockels cell. We built networks of as many as four of these transformer-capacitor (LC) networks; however, we were not able to generate more than two pulses reliably, and double pulses were generated reliably only at times during the laser pumping cycle predetermined by trial. The reason for this was not clear; no systematic study of possible reasons was attempted.

Passive Q-switching is accomplished by placing a cell containing a bleachable, reversible dye solution between the laser head and the 100% reflector, as in Figure 1. Cryptocyanine dissolved in methanol has the proper absorption characteristics for the ruby laser's fundamental wavelength of 6943Å. The metal ion occupying the center of the complex molecule in solution affects the exact location of the absorption band peaks and the relaxation rates (rates for the ion to return to its normal absorbent condition[7]). The concentration of the dye and the length of the cell ($\sim$ 1 cm for our arrangement) are so adjusted that cell transmission is approximately 50% when the photon density of radiation emanating from the rod is low. As pumping continues, the photon density rises rapidly, saturating the available ionic energy levels and the dye bleaches. Then, cavity gain increases rapidly and a giant pulse is generated before relaxation to normal absorbency occurs. Typical duration of a pulse is 10-30 ns, often much shorter than for pulses generated by electronic shutters.

In contrast to electronic Q-switching, it is relatively easy to convert from single-pulse operation to multiple-pulse operation when using passive Q-switching. One need only adjust either the dye concentration or the laser pumping voltage.

Control of jitter (uncertainty in the time giant pulsing occurs) is important for these experiments. In practice, we have found that for careful control of the dye concentration and pumping voltage, a jitter of less than ± 10 μs was common for both the single-pulse and multiple-pulse modes, somewhat better than the specification of ± 50 μs quoted by most manufacturers. To a lesser extent, the number of pulses

and their separation could also be regulated by careful attention to these variables, but control of jitter is much more reliable. We feel that some improvement of the pulse train characteristics may be possible by controlling the temperature of the rod more closely and, perhaps, by also regulating the dye temperature.

C. Camera

To make the interferograms, the Mach-Zehnder optical interferometer was backlighted by the sequence laser light source, as shown on Figure 1. [Notice that we use as a light source the laser beam focused onto frosted glass (after passing through a filter to decrease beam intensity). We have found this practice helpful in decreasing the deleterious effects on interferogram quality of air ionization at the focal point, beam non-uniformity, graininess, and large source size.]

The high speed camera on Figure 1 is slitless and shutterless. It consists of lens, L_3, and a rotating 4-sided mirror which sweeps images of the laser-illuminated event onto a stationary strip of film $\sim$ 240mm wide x 3m long. The film drum is located $\sim$ 1.04m from the front surface of the rotating mirror resulting in a test area magnification of $\sim$ 0.88. Commercial high speed panchromatic film (ASA 1250), with an extended red sensitivity, was used to record the interferograms.

The mirror is rotated by a cone-shaped turbine driven by bottle gases. The turbine is unique in that the driving gas also serves as a fluid bearing. For this experiment, we used $\sim$ 4 atm nitrogen to drive the mirror at $\sim$ 75,000 RPM-- a writing speed on the film of 16.2mm/μs or, for our optics, a framing rate of $\sim$ 100,000 frames/s. Much faster framing rates would be possible by reducing image size.

A problem associated with the camera was that the mirror was fully spun up before the experiment, so its orientation could not be controlled. As a consequence, one or even two photographs could be lost, because a section of the film drum had been removed at L_3 to allow the incident beam to pass -- not a full 180 degree arc.

D. Synchronization

For ideal synchronization of this experiment, the first laser pulse should be generated several microseconds after the shock wave emerges from the jet tube. Subsequent laser pulses should be of equal intensity with precisely-set spacing between pulses, and the duration of the pulse train should be tailored to prevent over-run (i.e., a second exposure of the film by late pulses).

Historically, we used the dye-controlled shutter first. Using it, we had a reasonable degree of success. The photographs shown in Figure 5, which were made for the first three laser pulses in Figure 3,

attest to that assertion (see also, later discussion of results). We achieved that success despite the fact that: 1) the shutter cannot be triggered precisely (electronically), 2) pulse train characteristics cannot be electronically uncoupled from one another, and 3) there is no signal (other than the first laser pulse) for use in synchronizing peripheral events. [All of these characteristics should, at least in principle, be achievable using an electro-optic shutter.]

When using the dye-controlled shutter, we found that we could predict onset of lasing much more accurately than we could predict when the shock wave would emerge from the tube. Therefore, we found it best to first adjust for several laser pulses, then to set timing so that the expected time of shock exit would be bracketed by the pulse train. For these experiments, duration of the pulse train could not be more than 185 μs (the time for the mirror to complete a sweep of the film) or the film would be doubly-exposed. To prevent this over-run, duration of the pulse train was usually tailored by readjusting the dye concentration, although sometimes a slight adjustment of pumping voltage was also necessary.

In an attempt to improve pulse train characteristics--decouple over-run from the other characteristics--and to increase the precision possible in synchronizing lasing onset with shock wave emergence, we tried multiple-pulsing of a Pockels cell. However, as described earlier in this section, that electronic Q-switch produced only two pulses reliably--often of unequal intensity, which could not be generated to coincide with the variations from run-to-run of the time that the shock wave would emerge from the tube. If we had been able to synchronize our experimental event to the pre-determined time of double-lasing, as can be done in many experiments, this method might have been useful, although it would be desirable to generate more pulses.

We also used the Pockels cell to trim the laser pulse train controlled by the dye concentration. We operated the Pockels cell (located in the laser cavity) in both the pulse-on and pulse-off modes using a DC voltage of several ms duration. In the pulse-on mode, we were able to suppress lasing onset until after the shock wave had emerged from the tube; in the pulse-off mode, we suppressed late pulses to prevent over-run. The latter technique was more useful, but in both modes, higher pumping energy was needed and pulse train characteristics became more capricious. Consequently, we abandoned this technique and used the dye shutter exclusively, paying closer attention to the regulation of dye concentration and laser pumping voltage.

It should be mentioned here that one of the most troublesome features of using a laser as a light source for photographing high speed flows is that pumping usually requires 500-1000 μs-irrespective of the method of Q-switching. Since the laser pumping time is on the

order of the time to generate the flow in this experiment, the passive technique described here is better-suited to a transient event which can be triggered reliably after flashlamp pumping has started, or even after the first giant pulse (using the pulse as a trigger). The above precautions notwithstanding, it should again be emphasized that our success ratio was quite good, despite the fact that our events could not be precisely-controlled.

III. DISCUSSION OF RESULTS

As mentioned briefly in the introduction, our purpose in making photographs of transient jet development--aside from being able to see the qualitative development of the flow field--was to obtain quantitative data from them. That is, we want to: 1) map the instantaneous contours of constant density for the entire flow field at different stages of development, and 2) measure the motion of the shock waves. We have found from other work[8] that it can be important to the accuracy of the quantitative data that a set of data be obtained for the same initial conditions. It would be ideal if all photographs could be made for the same run. However, that was not always possible. Some of the problems we encountered in obtaining useable data (photographs of good optical quality), and features of the flow field, will be discussed next.

A. Photograph Quality

Using the techniques described above, we made four runs using a select optical quality ruby rod (*circa 1970*) from which we got three useable sets of sequence interferograms (three runs). The best set (based on timing of the laser pulse train relative to shock emergence) is shown in Figure 5.

For all the runs made in this series of four runs, the laser pumping voltage was approximately the same, only small "fine-tuning" adjustments of voltage were made. [Dye concentration is adjusted for the larger changes.] Our results show that care had to be taken when adjusting the laser pulse train not to dilute the dye to such an extent that too many pulses were generated. In that event, many of the pulses were too weak to cause adequate exposure of the film.

To promote uniformity of flow field illumination, we chose to focus the laser beam onto a diffuser (frosted glass or frosted quartz).

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8. F. H. Oertel, Jr., "Investigations of Transitional Ballistics in a Muzzle Jet Flow Simulator," Proc. First Int'l. Sym. on Ballistics, Orlando, FL, Sec. II, p. 57, 1974.

If no diffuser were used, the requirements for uniformity of illumination in the far field would be even more stringent than those for our select quality rod. Without the diffuser, the field of a static mode photograph (no mirror rotation) was "blotchy". With it, even ordinary quality rods produced a good static mode photograph. However, care had to be taken to select a diffuser or a spot in that diffuser which gave good image quality.

Image quality for a run was estimated in the static mode by using a small ($\sim$ 1 mw) He-Ne gas laser--used also to align the laser axis to the optical system--to illuminate the diffuser while viewing the image in the film plane. If we had been able to use pulses with longer exposure times, moving the diffuser in the plane of the source (oscillation or rotation) would result in better quality photographs, because the grain pattern in the diffuser would be blurred. [Reducing grain is important, because we plan to use an automatic fringe reader which identifies the edge of each fringe as a difference in contrast. A large number of spurious readings due to grain could be a serious problem.] But, such tricks are not possible for our ultra-fast exposure times, because the grain pattern is "frozen".

Duration of the light pulses is also very important for obtaining good quality photographs of this highly transient gasdynamic process. For example, in the static camera mode, if the pulse duration is $\sim$ 2 μs, as for a BH-6 mercury arc source commonly used for interferometry or for a crowbarred spark light source, a shock wave moving at a velocity of 2000 m/s will move 4mm on a fixed piece of film (shadow photograph) during the exposure time, too much for resolution of the shock wave. For our nanolite and for the laser, the exposure times were $\sim$ 1/50 that of such a source, so that shock movement was only a fraction of a millimeter. This problem of pulse duration is even more critical for swept image photography (dynamic mode) using the rotating mirror. At a mirror rotational speed of $\sim$ 80,000 RPM, the writing speed on the film is $\sim$ 17mm/μs. For a pulse duration of 30 ns, the image will be smeared for $\sim$ 1/2mm, which we have found to be satisfactory for resolution of the interference fringe pattern.

We have noticed pulses of 30ns duration and shorter for our ruby rod of select optical quality when Q-switched with the dye shutter. For ordinary rods, duration of the pulses is usually much longer (especially since we must operate at energies considerably above threshold where many oscillation modes are excited in the ruby rod). Photographs made with pulses from these rods exhibited objectionable streaking of the grain pattern at the mirror rotational speeds used. An example is shown in Figure 6. Note in particular the indistinct outline of the jet tube at the left of the photograph. The length of the streaks indicates that for about two hundred nanoseconds the laser pulse was energetic enough to expose the film. Streaking of the grain was seen for our select rod for only a few images out of several dozen. And, in no case was the streaking objectionable.

We made no photographs using our electronic (Pockels cell) shutter; however, it is well-known that Pockels cells and (especially) Kerr cells produce pulses of longer duration than the dye cell. Consequently, we expect that streaks would also be likely when using conventional electronic shutters at our high film writing speeds.

B. Features of the Photographs

For completeness, we include a few remarks on the interferograms. The interferograms in Figure 5 show the fringe pattern typical of the Mach-Zehnder optical interferometer**: alternate light and dark fringes which are straight and parallel in the undisturbed receiver gas. Each fringe shifts in the disturbance (as one moves from right-to-left along a fringe). The initial upward shift is due to an increase in density through the outer shock wave.

The amount each fringe shifts relative to its position in the undisturbed gas, known as fringeshift, is related to the density through the well-known fringeshift equation[3], which can, in principle, be integrated for two-dimensional and axisymmetric flow geometries.

Since fringeshift can be affected by changes in geometry as well as by changes in density, the fringe patterns on the axisymmetric interferograms in Figure 5 should be interpreted with caution. However, this precaution notwithstanding, several features of the flow field can be inferred from these photographs. As mentioned earlier, the location of the expanding shock wave at the time each pulse illuminated the flow is clearly indicated by a sharp upward fringeshift when one moves from the straight, parallel fringe pattern of the undisturbed receiver gas into the disturbance. Within the disturbance, there is a rather sharp increase in the fringeshift evident in the last two photographs, as one moves from the tube in the flow direction. This is the recompression shock (Mach disc in the steady-state case)[5] which serves to recompress the rapidly-expanded tube gas, increasing its density. On the first photograph, we see the early formation of the recompression shock near the lip of the tube whose development can be followed in the subsequent photographs.

***The Mach-Zehnder optical interferometer operates on the principle of ray amplitude division. That is, parallel light from the source is divided by the interferometer's beam splitter so that approximately one-half the amplitude of each ray passes through the test section while the remainder of each corresponding ray passes through a reference medium. Having traversed different optical paths, a phase difference exists between corresponding rays so that when they are recombined at the film plane optical interference occurs--constructive interference (light fringes), destructive interference (dark fringes).*

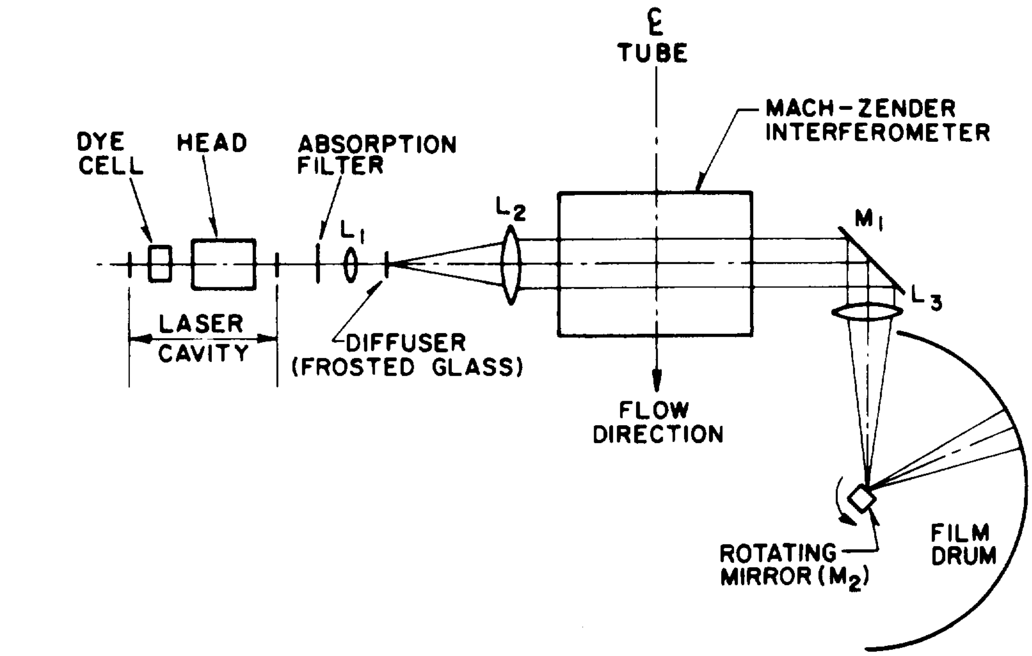


Figure 1. Plan View of the Experimental Setup; Jet Tube Location, Multiple-Pulse Laser, Mach-Zehnder Interferometer, and High Speed Camera

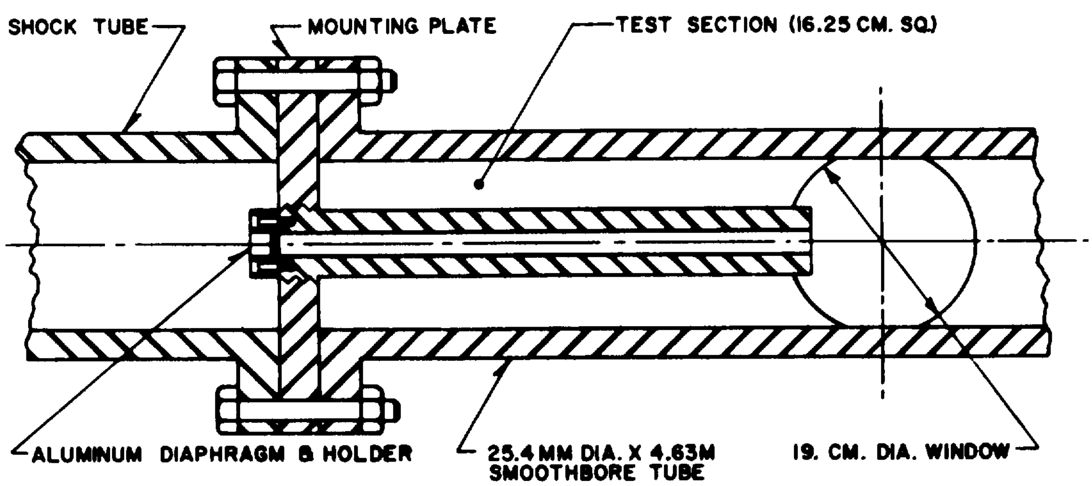


FIGURE 2. Location of the Jet Tube

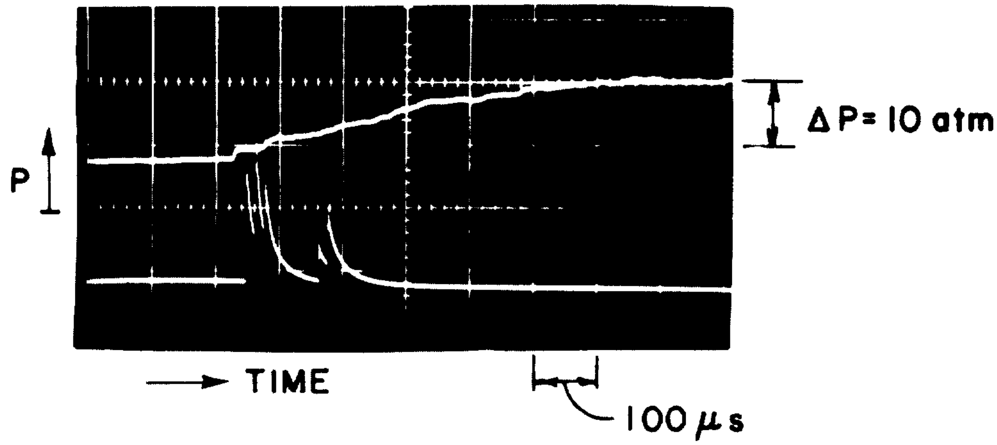


FIGURE 3. Simultaneously-Triggered Dual Beam Oscilloscope Traces: Upper Trace--Static Pressure Near the Tube's Exit Plane; Lower Trace--Multiple-Pulse Sequence (Laser Pulse Train)

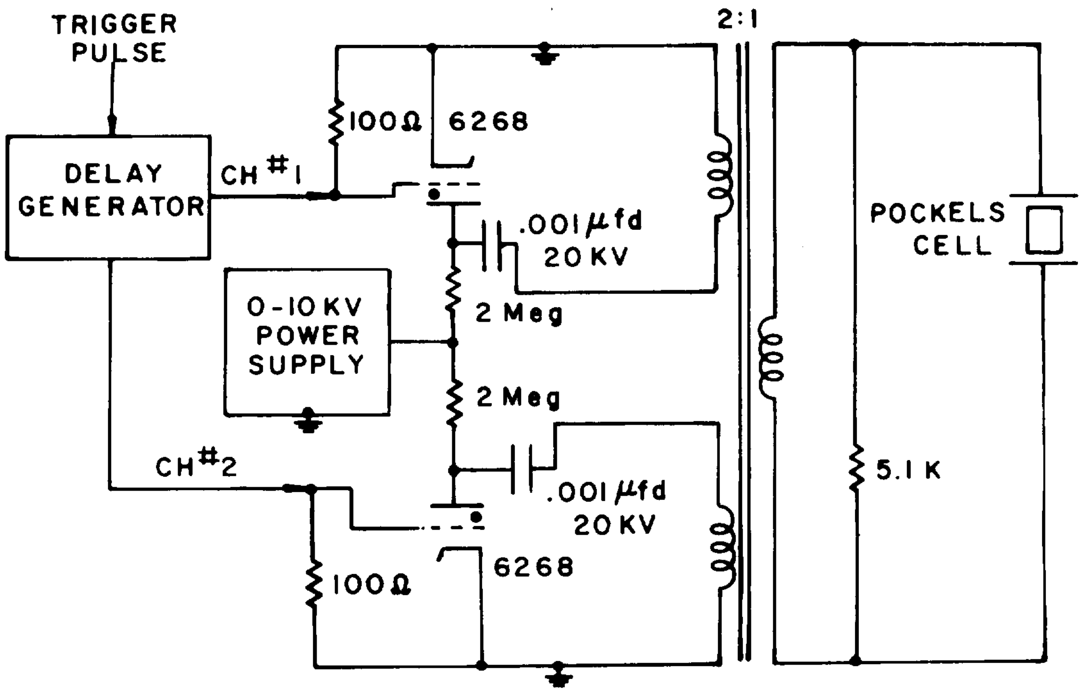
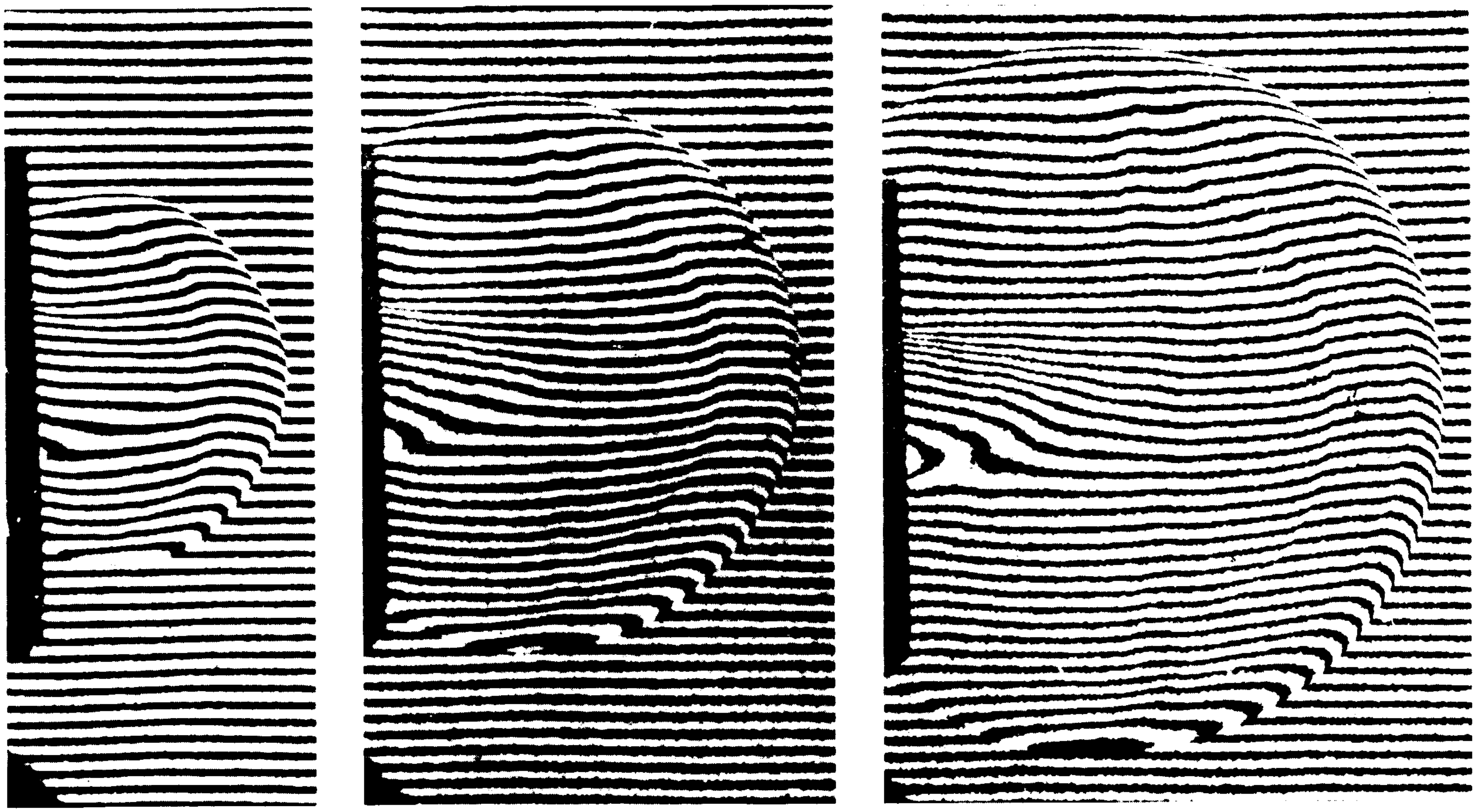


FIGURE 4. Schematic of Double-Pulse Shutter Driver



a. 20 μs   b. 35 μs   c. 49 μs

Figure 5. Sequence of Multiple-Pulse Laser Interferograms for a Single Run in Air. Elapsed Times after Shock Emerges are Shown. λ = 6943Å, Shock Mach Number at Exit, $M_s \sim 4.5$; Ratio of Exit Pressure to Ambient Pressure, $p_e/p_\infty \sim 75$; Mach Number Behind at Exit, $M_e > 1$.

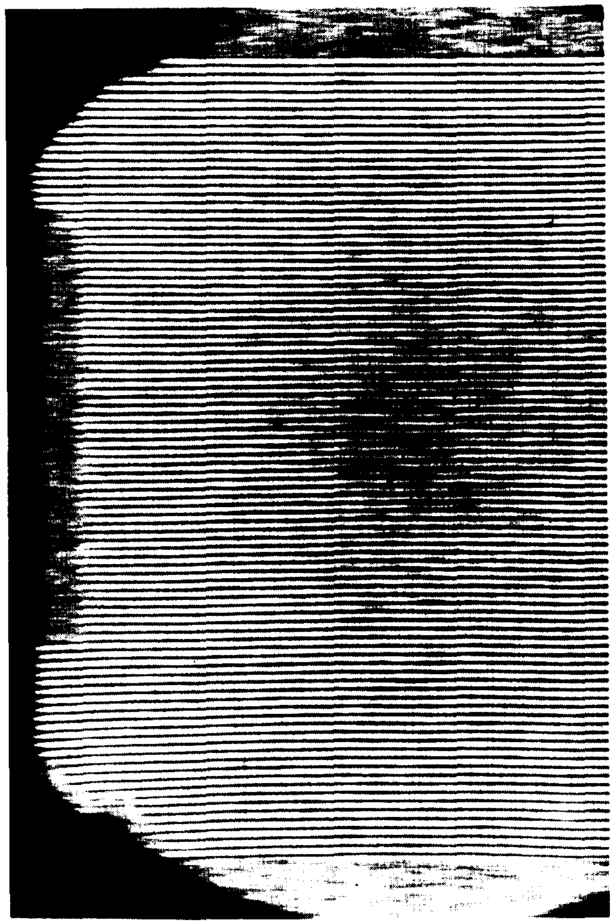


Figure 6. Single Frame from a Sequence of Multiple-Pulse Laser Interferograms (no flow from tube). λ = 6943Å; Writing Speed $\sim$ 17mm/μs

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